

IH for the CSP 7: Relative Humidity Or, the Psychrometric Chart

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Abstract

A given sample of air can hold varying amounts of moisture depending on its temperature. The higher the air temperature, the more moisture it can contain. The relative humidity is the fraction of the maximum moisture capacity actually present in a sample of air. Relative humidity is the measure of moisture content that best correlates to our perception of "mugginess." There are many inexpensive direct-reading instruments which will display relative humidity. They are readily available in nearly every department store. Unfortunately these simple instruments lack precision and would be extremely difficult to calibrate. In order to make precise measurements of relative humidity (such as needed to assess heat stress), Industrial Hygienists use a device called a psychrometer. Relative humidity must be interpreted using psychrometer readings and an appropriate psychrometric chart.

The dew point is the temperature at which a sample of air with the same moisture content as a given sample would be at 100% relative humidity. The temperature at the 100% relative humidity curve is the dew point. The relative humidity can never be greater than 100%. (Why?) If the temperature of a mass of air is lowered below the dew point, it can not hold all the moisture it held previously, and water must fall out, settling as liquid on the ground. Therefore, when the temperature of air goes below the dew point, the dew begins to form on the ground, hence the name. The dew point is a measure of the moisture content in the air. If the actual temperature is near the dew point, the air feels very humid. However, if the air temperature is well above the dew point, the air feels very dry.

Unit Conversions

As there are so many psychrometric charts available, it is often difficult to find one expressing temperatures, moisture content and other variables in the units desired. It is usually quicker and easier to use the first chart you find with the proper ranges of temperatures, read the desired values from the chart, and convert units.

Even before heat was recognized as a form of energy, it was known that heat moved from objects of higher temperature to objects with lower temperature. In order to quantify temperatures to study this phenomenon, two points on a scale had to be fixed. Two common things with relatively fixed temperature values were icy sea water and the human body. Early thermodynamic investigators defined the temperature of icy sea water to be zero degrees, and the human body to be 100 degrees. This was the origin of the Fahrenheit scale. Further study showed that both of these temperatures could

vary. A more precise definition of temperature was required. Two temperatures known not to vary, were the freezing and boiling temperatures of pure water at one atmosphere. The freezing temperature was defined as zero degrees, and the boiling temperature was defined as 100 degrees. This was the origin of the Celsius scale. To avoid confusing temperatures measured on one scale with those measured on the other, the notation $^{\circ}\text{F}$ was used for the Fahrenheit scale, and $^{\circ}\text{C}$ was used for the Celsius scale.

We now know that pure water boils at 212°F , and freezes at 32°F . This allows us to convert from one scale to the other. To convert Fahrenheit to Celsius, we first must shift the "zero" point on the scale. Since pure water freezes at 32°F , we must subtract 32° from the Fahrenheit temperature. Next we observe that the difference in the freezing and boiling points is 100°C (by definition), but is 180°F ($212^{\circ} - 32^{\circ}$). In other words, a difference in temperature of 100°C equals a difference of 180°F , or by dividing, a difference of 5°C equals a difference of 9°F . Therefore to convert $^{\circ}\text{F}$ to $^{\circ}\text{C}$, we subtract 32, then multiply by $5/9$.

Notation is always confusing when changing between temperature scales. The actual temperature, T , of an object does not change if we measure it on different scales. It is just as cold or hot regardless of how we measure it. For instance if we write,

$$T = (T-32) 5/9 ,$$

this is simply an algebraically false statement, unless $T = \pm \infty$.

The best notation to use is the parenthetical notation. In the parenthetical notation, the variable is simply a number. The units to go with that number to make it a measurement are given in parentheses. For instance, $T(^{\circ}\text{C})$ is read, "the temperature in degrees Celsius." Using this notation,

$$T(^{\circ}\text{C}) = 5/9 [T(^{\circ}\text{F}) - 32] ,$$

and

$$T(^{\circ}\text{F}) = 9/5 (T ^{\circ}\text{C}) + 32 .$$

Notice to convert Fahrenheit to Celsius, subtract first, then multiply. To convert from Celsius to Fahrenheit, multiply first, then add.

Unfortunately, our confusion with temperature scales does not end here. The zero degree points on both the Fahrenheit and Celsius scales were arbitrarily chosen. When we later realized how temperature was related to heat energy, we observed that neither 0°F nor 0°C represented objects with no heat. Two more temperature scales were devised such that if an object had a temperature of zero on these scales, it had no heat energy. Zero degrees on either of these scales is referred to as "absolute zero." It

is the coldest any object can possibly be. The absolute scale associated with the Fahrenheit scale is the Rankin scale. Zero on the Rankin scale is -460°F , or

$$T(^{\circ}\text{R}) = T(^{\circ}\text{F}) + 460 .$$

Similarly, the absolute scale associated with the Celsius scale is the Kelvin scale,

$$T(^{\circ}\text{K}) = T(^{\circ}\text{C}) + 273.15 .$$

Converting from Rankin to Kelvin is relatively easy. Zero on both scales refers to the same temperature (absolute zero).

$$T(^{\circ}\text{K}) = 5/9 T(^{\circ}\text{R}) \text{ and } T(^{\circ}\text{R}) = 9/5 T(^{\circ}\text{K}) .$$

The absolute scales have many uses. For instance, in the ideal gas law,

$$PV = nRT ,$$

temperature must be measured on an absolute scale.

The water content of air is an important variable when assessing heat stress. It can be expressed in a great number of ways. Surprisingly, on charts using the English system of measures the most common unit for moisture capacity is grains (gr) of water per pound-mass (lbm) of dry air. This called a "mass ratio." Be careful with this notation "gr" is often mistaken for gram. One pound-mass equals 7,000 grains. Therefore,

$$\text{grain of H}_2\text{O per lbm of dry air} = 1.43 \times 10^{-4} \text{ lbm of H}_2\text{O per lbm of dry air},$$

Since the units of mass will cancel out of the right hand side of this equation, one grain of H₂O per lbm of air can be thought of simply as 1.43×10^{-4} . For example,

$$\text{grain of H}_2\text{O per lbm of air} = 1.43 \times 10^{-4} \text{ kg of H}_2\text{O per kg of dry air}.$$

In the metric system, a common unit is grams (g) of water per kilogram (kg) of dry air. Since $\text{kg} = 1,000 \text{ g}$, this becomes,

$$\text{gram of H}_2\text{O per kilogram of dry air} = 10^{-3} \text{ kg of H}_2\text{O per kg of dry air},$$

and,

$$\text{grain of H}_2\text{O per lbm of dry air} = 0.143 \text{ grams of water per kilogram of dry air}.$$

The equation directly above now gives us a conversion factor to convert grains of water per pound-mass of dry air (English Units) to grams of water per kilogram of dry air (Metric Units).

Another useful way to express moisture content (as you will see in the next article in this series) is the partial pressure of water in air, often abbreviated PW. Conversion from a mass ratio to a partial pressure is a bit more complicated. The pressure exerted by an ideal gas does not depend on its mass. Therefore we must convert mass into moles.

The molecular weight of water is 18 (16 for one oxygen atom and one for each hydrogen atom). Therefore one gram-mole (g-mole or simply "mole") of water vapor weighs 18 grams. The molecular weight can be thought of as a conversion factor from mass to the number of moles. For example, the molecular weight of water can be thought of as 18 g/g-mole. Similarly, one lb-mole weighs 18 lb, and a kg-mole weighs 18 kg. Dry air is approximately 21% diatomic oxygen (MW=32), 78% diatomic nitrogen (MW=28) and 1% other gases, e.g. argon, carbon dioxide, etc. The average molecular weight of dry air is approximately 29. To convert from a mass ratio to a volume ratio we "convert" mass to moles. Remember to keep track of the mass units.

Substituting, we have

$$\begin{aligned} \frac{\text{gr of H}_2\text{O}}{\text{lbm dry air}} &= \frac{1.43 \times 10^{-4} \text{ lbm of H}_2\text{O}}{\text{lbm of dry air}} \cdot \frac{\text{lbm-mole H}_2\text{O}}{18 \text{ lbm H}_2\text{O}} \cdot \frac{29 \text{ lbm dry air}}{\text{lbm-mole dry air}} \\ &= \frac{2.30 \times 10^{-4} \text{ lbm-mole H}_2\text{O}}{\text{lbm-mole of dry air}} \end{aligned}$$

The equation above gives us the ratio of water to dry air, not the ratio of water to total air. Suppose we found from the psychrometric chart that our workplace air contained 110 grains of water per pound-mass of dry air. The ratio would then be,

$$\frac{110 \text{ gr of H}_2\text{O}}{\text{lbm of dry air}} = 110 \cdot \frac{2.30 \times 10^{-4} \text{ lbm-mole H}_2\text{O}}{\text{lbm-mole of dry air}} = \frac{0.0253 \text{ lbm-mole H}_2\text{O}}{\text{lbm-mole of dry air}}$$

The total number of moles of moist air that would contain 110 gr of water is 1.0253 lbm-moles. The water content expressed as a percent of total pressure is therefore,

$$\% \text{ of total pressure} = \frac{0.0253}{1.0253} = 0.0247 = 2.47 \% .$$

We can now easily calculate the partial pressure of water in any desired units by multiplying one atmosphere by this fraction.

$$1 \text{ atm} = 760 \text{ mm Hg} = 29.92 \text{ " Hg} = 760 \text{ torr} = 14.7 \text{ psi}$$

For our example if workplace air contains 110 grains of water per lbm of dry air, the partial pressure of water (PW) = 18.7 mm Hg = 0.36 psi.

The Psychrometer

The psychrometer is a device used for measuring the moisture content in air, as well as air temperature. It consists of two thermometers, one dry, and one with a wet wick placed over the bulb. Thermometers are precise, accurate, and consistent, all required for measurements to be admissible in court. Although more expensive, thermometers are available with calibration traceable to the National Institute of Standards and Technology (formerly the National Bureau of Standards). Air is forced over the thermometers, either using a fan or by spinning the thermometers about a pivoted joint. Because the thermometers are spun in the same manner as a sling, such as the one David used to slay Goliath, the device is often called the "sling psychrometer." The temperatures measured are referred to as the dry bulb temperature and the wet bulb temperature. To avoid confusion with the natural wet bulb temperature measured by the WiBGeT heat stress monitor, the wet bulb temperature is often called the forced wet bulb temperature. The wet bulb temperature may be thought of as the lower limit on the natural wet bulb temperature as air velocity increases.

When air is forced over the wet bulb, water will evaporate at a rate depending only on the temperature of the bulb and the humidity of the air. When air is relatively dry, heat lost by evaporation causes the forced wet bulb temperature to be significantly lower than the dry bulb temperature. When there is more humidity, water will evaporate at a relatively slower rate, and there will be a smaller difference between the wet and dry bulb temperatures. If the air is completely saturated (100% relative humidity), there will be no evaporation at all, and the wet bulb temperature will equal the dry bulb temperature.

The Psychrometric Charts

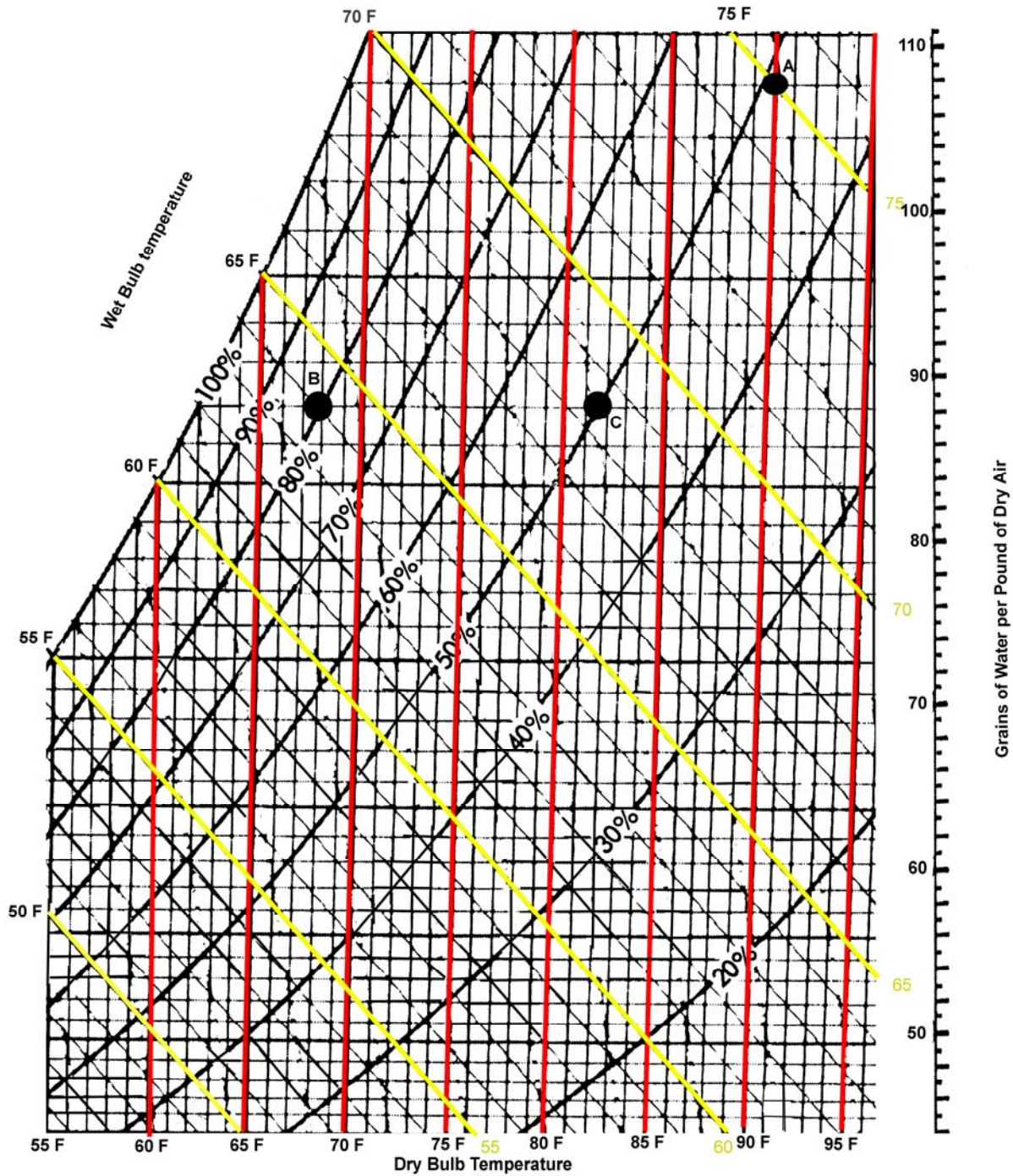
The behavior of water in air is very complicated. There is no simple set of equations which may be used to calculate the parameters of interest, such as the total moisture capacity, various measures of moisture content, relative humidity, dew point, enthalpy (energy), pressures, temperatures, etc. All these parameters must be read from the psychrometric charts.

There are a great many published psychrometric charts. A wide variety is available on [Google Images](#). The charts can show any variety of variables and different ranges in any of those variables. The concept behind all these charts, however, is the same. Each chart is made up of sets of nearly parallel contour lines, forming a grid. Usually three or four sets are used, but some charts contain more. Each set of nearly parallel lines denotes some variable, such as the dry bulb temperature, wet bulb temperature, relative humidity, etc. The values for any two variables must be known to specify the condition of a sample of air. The point on the chart where the particular lines representing those two values cross is the point representing the condition in question. This point is called the "location" of the given condition in "phase space." Once the proper point is located on the chart, the values of all other variables can be read from

the other contour lines.

The psychrometric charts are very analogous to elevation contour maps. A contour map is made by overlaying three sets of nearly parallel lines; latitude, longitude, and elevation. The vertical lines show longitude. Any two points on the same vertical line have the same longitude. The horizontal lines show latitude. Any two points on the same horizontal line have the same latitude. The third set of lines show elevation. These lines are only roughly parallel and can curve and bend. If a hilltop is represented, the contour lines are concentric circular shapes. If the longitude and latitude of a given location are known, the point on the map representing that location can be found. The altitude can then be read from the third set of contour lines.

Refer to the psychrometric chart below. This chart is especially useful to industrial hygienists. The chart covers the range of temperatures and moisture content usually encountered in workroom air in hot environments. The chart applies to air at one atmosphere (standard pressure) only. If samples of air are at other pressures, it can not be used.



This chart has four sets of contour lines. The vertical lines represent the dry bulb temperature of air, the conventional temperature. Major dry bulb lines (even multiples of 5 °F) are shown in red. The horizontal lines represent the moisture content of the air, measured in grains of water per pound of dry air (gr/lb) or dew point.

The diagonal lines running down and to the right represent the wet bulb temperature (forced wet bulb). Major wet bulb lines (even multiples of 5 °F) are shown in yellow. The fourth set of contour lines represents relative humidity. Lines of constant relative humidity arch up and to the right.

Example

Consider the following example. Suppose the dry bulb temperature (or simply "the temperature") of air in a given room is 90 °F and the wet bulb temperature is 75 °F. A vertical line is imagined extending straight up from the value "90 °F" on the bottom axis (dry bulb). A second line is imagined extending down and to the right from 75 °F on the upper axis (wet bulb). The point where these two lines cross is shown as point A on the figure. This point represents the condition of the air in this room. Now that the state of the system is specified, we may determine the moisture content, dew point, and relative humidity. To find the moisture content, a horizontal line is extended from the point specifying the system to the axis on the far right. This line intersects the axis at approximately 108 gr/lb. By extending the same line to the far left, the dew point is observed to be 69 °F. Next observe that the point defining this system falls slightly below on the curved line labeled "50%." The relative humidity in this example is interpolated to be about 48%.

Notice that the wet bulb temperature equals the dry bulb temperature at the 100% relative humidity contour, also called the "dew point line." This must be the case because at 100% humidity there will be no evaporation to cool the wet bulb. The dew point for a given sample of normal workroom air will depend only on the moisture content. Therefore, providing both the dew point and the moisture content will not define the state of the system, i.e. you can not determine the web bulb or dry bulb temperatures given only the dew point and moisture content. We call the dew point and moisture content "redundant" information, even though these two values may be used in different ways.

The psychrometric charts can also be used to determine how the other parameters will be affected when one parameter is changed. Many, many extremely complicated problems in industrial ventilation can be solved at a glance using the charts. The technique is very simple. Decide what parameter must remain constant. Think of the point on the chart which describes the conditions of the air sample. Think of the point as sliding back and forth along the line corresponding to the given value of the constant parameter. Slide the point along the constant contour until it reaches the line corresponding to the new value of the changing parameter. Finally, read off the values of all other parameters from this new location of the system point.

Consider this example. The temperature in the banquet hall is a comfortable 68 °F. The relative humidity, however, is a sticky 80%. The pastry chef is pitching a fit because his stuffed crepes lack crispness by the time they are served. If the relative humidity is not reduced to 50%, he threatens to slam the oven door, flattening the

soufflé. Suppose you have no means of removing the moisture content (no dehumidifiers or air conditioning), but can raise the temperature of the room using the heaters. To what temperature (dry bulb) must the room be raised to lower the relative humidity to 50%?

The point representing the initial conditions in the room is located on the psychrometric chart. This is labeled point B on the chart. Point B is imagined sliding directly to the right (along the 62 °F dew point line) until it reaches the 50% relative humidity curve. This point is labeled C on the chart. The required temperature is seen to be 83 °F. (Verify the location of these points and read the dry bulb temperature.) Since this temperature is unreasonably high, you tell the chef where to stuff his crepes, and take your chances with the soufflé.